

Method and apparatus for measuring a depth of holes in composite-material workpieces being machined by an orbiting cutting tool

5 Technical Field

The present invention relates to a method and an apparatus for measuring a depth of a hole in a composite-material workpiece being machined by a rotating cutting tool orbiting about a principal axis. The invention is, in particular, useful when making
10 holes in multilayered workpieces, for example in various fiber-reinforced composite materials, laminates or material stacks comprising at least two layers material for use in the aircraft and space technologies.

15 Background of the invention

For example, in aircraft multilayered components the thickness thereof may vary along the extent of the workpiece and thus the depth of the holes being formed therein may vary accordingly. It is important to accurately determine the individual
20 depth of each hole being formed so as to be able to properly match the hole with an individual, accurately fitting fastener, such as a bolt or a blind fastener. Also, it is desirable to minimize the axial movement of the cutting tool in order to avoid unnecessary drilling in the air after having penetrated the workpiece.

25 A previous method of detecting the initial contact between a cutting tool and the surface of the workpiece and to determine when the cutting tool reaches various interfaces and depths of a multilayered workpiece is disclosed in the US patent specification No. 4 644 335. This method involves the steps of detecting and analyzing output signals as to the acoustic signatures thereof, e.g. waveforms, amplitudes and
30 frequencies of the output signals. However, such measuring methods are sensitive to disturbances and interferences caused by and transferred from mechanical working operations being performed simultaneously on other locations of the same workpiece. This may jeopardize the reliability of the measuring results of the depth in the
35 respective hole.

Summary of the invention

It is an object of the invention to eliminate the drawbacks of previously known methods and to provide a novel method and apparatus capable of determining the exact initial position of contact (a first zero reference position) between an axial cutting edge of a cutting head of the cutting tool and a first surface of the workpiece and to determine the exact position when radial cutting edges of the cutting head has fully penetrated the opposite, second surface of the workpiece. The distance between the point of entrance and the point of exit of the cutting head in the workpiece (the depth of the hole) may be calculated by means of a measuring means for measuring the axial movement of the spindle unit and the cutting tool, e.g. a linear encoder built-in to the machine tool.

According to one aspect of the present invention this could be carried out by deducting a predetermined axial length of the radial cutting edges of the cutting head having penetrated the workpiece from the total length of axial advancement of the cutting tool from the first zero reference position to the point where the cutting head breaks of an electric circuit through the workpiece. More specifically, the method of claim 1 comprises the steps of:

- a) applying a low-level electric potential to an electrically insulated cutting tool, the cutting tool having a longitudinal center axis and a cutting head with radial and axial cutting edges and with a predetermined axial length;
- b) rotating the cutting tool about the longitudinal axis;
- c) axially advancing the cutting tool towards the workpiece;
- d) determining a first zero reference position of the cutting tool as it initially makes contact with a first outer surface of the workpiece and thereby closing an electric circuit through a grounded workpiece;
- e) keeping a measuring means for measuring an axial movement of the cutting tool activated from the first zero reference position;
- f) performing an orbital rotation of the cutting tool about a principal axis;
- g) axially feeding the cutting tool into the workpiece;

- h) monitoring a specific character of the electric potential during the advancement of the cutting tool through the workpiece;
- i) detecting the point of breaking of the electric circuit when the cutting head of the cutting tool penetrates an opposite, second surface of the workpiece; and
- 5 j) determining by help of the measuring means the depth of the hole by deducting the predetermined axial length of the cutting head having penetrated the workpiece from the total length of axial advancement of the cutting tool from the first zero reference position to the point of breaking of the electric circuit through the workpiece.

10 According to another aspect of the present invention the depth of the hole being produced can be calculated by also determining a second reference position of the cutting tool by axially backing the cutting tool to make contact with the second surface of the workpiece after having penetrated the same so as to reclose an electric
15 circuit through the workpiece and ground. An accurate determination of the depth of the hole produced by the cutting tool may thus be obtained by the help of the two reference positions registered by the linear encoder. More specifically, the method of independent claim 2 comprises, in addition to the aforementioned steps a-i) the steps of:

- 20 k) performing a small incremental increase of the radial offset of the cutting tool;
- l) axially backing the cutting tool to make contact with the second surface of the workpiece for determining a second reference position of the cutting tool as it recloses the electric circuit; and
- 25 m) calculating the depth of the hole produced by the cutting tool by the help of the obtained two reference positions.

30 Furthermore, owing to the present method of sensing the exact position where the cutting head has fully penetrated the workpiece, it is also possible to minimize the axial movement of the cutting tool in order to avoid unnecessary drilling in the air of the cutting tool after the penetration of the workpiece.

Further features of the methods of the invention are set forth in the independent claims 3 and 4.

5 The present invention also relates to an orbital machining apparatus for producing a hole in a composite-material workpiece and measuring the depth of the hole being produced. The apparatus comprises the features set forth in the independent claim 5.

The invention will be further disclosed in connection with the following detail description with reference to the enclosed drawings.

10 **Brief description of the drawings**

Fig. 1 is a longitudinal section view of a previously known orbital machining apparatus having many basic components in common with the apparatus of the invention;

15 Fig. 2 is a detailed sectional side view of an electrically insulated spindle unit used in the orbital machining apparatus of the invention;

20 Figs. 2a and 2b are schematic side views of a cutting tool out of and in electric contact with a workpiece;

25 Fig. 3 is a schematic view of an orbiting cutting tool coming into initial electrical contact with a composite-material workpiece;

Fig. 4 is a view similar to Fig. 3 illustrating a position of the orbiting cutting tool when the cutting head thereof is just losing contact with the workpiece after having penetrated the same; and

30 Fig. 5 is a view similar to Figs. 3 and 4 illustrating the position of the cutting tool when the cutting head thereof has been somewhat radially displaced after the penetration of the workpiece and then brought into contact again with the workpiece.

Detailed description of preferred embodiments

5 In the method of the present invention for measuring the depth of a hole being machined in a composite-material workpiece an orbital machining apparatus 10 is used. The orbital machining apparatus 10 includes, like conventional orbital drilling machines, such as described in e.g. WO 01/15870 A2, WO 03/008136 A1, US-A-5 971 678, a first actuator in form of a spindle motor unit 12 configured for rotating a
10 spindle 13 and a cutting tool 14 having a longitudinal center axis 16 during the machining of the hole; a second actuator 20 configured for moving the cutting tool 14 in an axial feed direction towards and into the workpiece substantially parallel to the tool axis 16, the second actuator 20 being simultaneously operable with said first actuator 12; a third actuator 22 configured for rotating the cutting tool 14 about a
15 principal axis, the principal axis being substantially parallel to said center axis 16 of the cutting tool 14 and coaxial with a longitudinal center axis of the hole to be machined, the third actuator 22 being simultaneously operable with said first and second actuators 12, 20; and a radial offset mechanism 24 configured for controlling the radial distance of the center axis 16 of the cutting tool 14 from the principal axis.

20 As shown more in detail in Fig. 2, the spindle motor unit 12 comprises an electric motor, which may include an inner rotor 26 and an outer stator 28 with an air gap 30 therebetween. The apparatus 10 may be slideably mounted to a stationary stand 32 (Fig. 1) or mounted to a movable member, such as a robot arm (not shown). The
25 second actuator 20 includes an axial feed mechanism comprising a stationary motor 34 which drives a ball screw 36 engaging a ball nut 38 fixedly secured to a machine housing H. As the motor 34 rotates, the machine 10 will slide either forwardly or rearwardly on the stand 32 thereby moving the cutting tool 14 axially.

30 The radial offset mechanism 24 basically comprises an inner hollow cylindrical body 38 rotatably supporting the spindle 13 in an eccentric hole therein by means of ceramic bearings 40 which electrically insulate the spindle 13 from the surrounding

components of the machine. The eccentric hole has a longitudinal center axis that is parallel to but radially offset a distance from the longitudinal center axis of the inner cylindrical body 38. The eccentric inner cylindrical body 38 is, in its turn, rotatably supported within an axially extending eccentric hole of a second, outer hollow cylindrical body 42 (Fig. 1). The eccentric hole of the outer cylindrical body 42 has a longitudinal center axis that is parallel to but radially offset a distance from the center axis of the outer cylindrical body 36 (the principal axis). Preferably, the holes of the cylindrical bodies 38 and 42 have the same eccentricity, i.e. the hole center axes are radially offset the same distance from the respective center axis of the bodies 38 and 42. By rotating the inner cylindrical body 38 within the eccentric hole of the outer cylindrical body 42, or by a mutual, relative rotation of the cylindrical bodies 38, 42, it is thus possible to locate the center axis of the eccentric hole of the inner cylindrical body 38 such that it, and hence the spindle 13 and the center axis 16 of the cutting tool 14, will coincide with the center axis of the outer cylindrical body 42. In this case there is no radial offset at all of the cutting tool axis 16. By performing a mutual, relative rotation of 180° of the inner and outer cylindrical bodies 38, 42 away from this zero radial offset position, a maximum offset of the cutting tool axis 16 is obtained.

Basically, the outer cylindrical body 42 is rotatably supported in the housing H of the apparatus 10 and is rotatable by a motor (not shown) via a belt 46, which engages a belt wheel 48 connected to the outer body 42. Likewise, the inner cylindrical body 38 is rotatable by a further motor (not shown) via a belt 52, which engages a belt wheel 54 connected to the inner body 38 via a coupling 56. The belt wheel 54 is arranged to rotate in a concentric position relative to the belt wheel 48.

The machine 10 is equipped with a measuring means (not shown) for measuring the axial movement of the spindle 13, e.g. a linear encoder, which senses the axial position of the spindle 13 and the cutting tool 14 during the operation of the machine.

As shown schematically in Figs. 2a and 2b, the cutting tool 14 is connected to a low-voltage source U so as to apply an electric potential thereto. Fig. 2a illustrates a starting position of the cutting tool 14 wherein an electric circuit through the work-

piece W connected to ground is broken, while Fig. 2b illustrates the initial contact between the rotating tool 14 and a workpiece W, where an electric circuit is closed through the workpiece W thereby indicating a first zero reference position of the cutting tool 14.

5 The method of measuring the depth of a hole being machined in a composite-material workpiece W by an orbital drilling operation will now be described. As shown schematically in Fig. 2b and 3, when the rotating cutting tool 14 initially contacts the outer surface W_1 of the workpiece W, the electric potential applied to the cutting tool 14 will be connected to ground through the workpiece W. This indi-
10 cates a zero reference position of the tool 14 from which the depth of the hole will be calculated by help of the measuring means, such as a linear encoder associated with the machine 10. The hole machining procedure now starts with the rotating cutting tool 14 performing a conventional orbital movement, i.e. the tool 14 is ro-
15 tating also about a principal axis corresponding to the center axis of the hole, while a simultaneous axial movement is performed. As shown in Fig. 3, the cutting tool 14 used is preferably an end mill having a cutting head 57 with radially extending axial cutting edges 58 and axially extending radial cutting edges 60 which have an axial length L which is substantially less than the depth of the hole being made.

20 As seen in Fig. 4, when the cutting head 57 has penetrated the opposite surface W_2 of the workpiece W, i.e. as the rear end 62 of the radial edges 60 loses contact with the workpiece, the electric circuit through the workpiece W will be broken. This second reference position of the cutting tool 14 is registered by the measuring
25 means. Now, the depth d of the finished hole can be calculated by deducting the length L of the cutting head 57 (substantially corresponding to the axial length of the radial cutting edges 60 and the axial height of the axial cutting edges 58 having penetrated the workpiece) from the total length of axial advancement of the cutting tool 14 from the first zero reference position to said second reference position where
30 the electric circuit through the workpiece was broken.

Alternatively, as shown schematically in Fig. 5, the second reference position could be obtained or reconfirmed by performing a small incremental increase of the radial offset of the cutting tool 14 after the penetration of the cutting head 57 through the rear surface W_2 of workpiece W and then axially backing the cutting tool 14 to make a new contact with this surface of the workpiece. This indication of the second reference position by closure of an electric circuit may be obtained in a more distinct manner than at the break of the electric circuit.

The inventive method is applied to composite-material workpieces in general, such as workpieces consisting of fiber-reinforced composite materials, metal composite materials including metal-reinforced composites, metal-to-metal composites and metal-to-fiber composites or laminates or stacks of material layers. Composite materials as such comprise a plurality of material layers.

The methods of the present invention for measuring the depth of a hole in a workpiece may be partly used also for determining a desired depth of a countersink of a hole, where an integrated beveled countersinking portion of the cutting tool is used. Identifying the zero reference position and then advancing the cutting tool a length corresponding to the distance between the distal end of the cutting head and the distal end of the beveled countersinking portion, makes it possible to obtain a predetermined depth of the countersink. Also the depth of a blind hole may be obtained in a similar manner.